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PRINCIPAL INVESTIGATOR: James H. Bertera, Ph.D.

CONTRACTING ORGANIZATION: Schepens Eye Research Institute
20 Staniford Street
Boston, Massachusetts 02114

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FOREWORD

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INTRODUCTION

Central scotomas produce losses in visually guided performance because central vision has the best visual resolution compared to more peripheral retina (Ludvig, 1941), and central retina is important in stable eye positioning. Two basic deficits result from a central field scotoma. First, the scotoma blocks foveal information forcing a shift in target acquisition to the lower resolution peripheral retina. The second general form of basic effect from a scotoma is abnormal eye movement patterns which may be either compensatory, such as eccentric or off axis viewing, or drift movements due to loss of foveal fixation control (See Figure 1).

Scotomas and retina.

Significant losses in visually guided performance and abnormal ocular movements are not surprising with a foveal scotoma since the central region of the retina, the macula, and its center, the fovea, have the highest density of light receptors. The fovea is used for finer visual tasks like reading text, threading a needle, checking a gauge, or searching for small targets. Foveal vision is distributed around the visual display in pauses called eye fixations at about three per second. Each fixation is followed by a flicking eye motion called a saccade or eye movement which delivers the fovea to a new visual field location. Smooth, lower velocity eye movements are used to pursue moving targets or to compensate for head movement. Both slow and saccadic movements serve to stabilize a target of interest on the high resolution fovea.

Central or foveal visual loss is associated with retinal diseases like macular degeneration or retinal detachments and with trauma from impact, blood vessel changes, or the light damage associated with accidental exposure to laser light. An absolute central scotoma refers to a visual field area across the fovea that is completely unresponsive

to light. If the damaged area is large enough or if the cell loss is absolute, visual search, reading text or instruments, or any fine detail work, becomes difficult or impossible. The advantage of the simulated scotoma method is that the damage area can be exactly defined or changed at will and maintained for longer study in complete safety, without any contact with the eye or exposure to strong light sources. When the fovea is lost or compromised by accident, disease or laser exposure, subjects must adapt their eye position so that targets of interest are stabilized on spared regions of peripheral retina, rather than the reflexive habit of stabilizing targets on the fovea.

Scotomas and eccentric viewing

The simulated scotoma method uses the subject's own eye movements to electronically stabilize a simulated obscurant or mask across the fovea; the subjects must learn to adapt their eye fixation position and saccades in order to acquire targets from peripheral vision. This real time, eye-slaved scotoma allows control over the size, position and density (severity of injury) of the area of simulated visual loss. Further, the scotoma character can be varied over time to simulate tissue recovery processes, or maintained for extended periods like a severe injury.

Simulated scotomata in normal human subjects as well as retinal or neurological lesions in patient populations produce strong adaptive responses and impairments in basic functions of the visual system. When artificial central scotomata are positioned across the fovea there is an increase in contrast sensitivity thresholds (Kelly, 1972; Higgins, Coletta and de Monasterio, 1983), a reduction in the motor component of convergence and divergence responses (Kertesz and Hampton, 1981; Boman and Kertesz, 1985), and slowed reading and increased eye fixation duration (Rayner and Bertera, 1979). Bertera (1988) used a simulated scotoma to examine the effects of loss of central vision on visual search time, eye fixation duration and saccade length. The results showed that a 10 or 20 minarc simulated foveal scotoma could increase both visual search time and eye

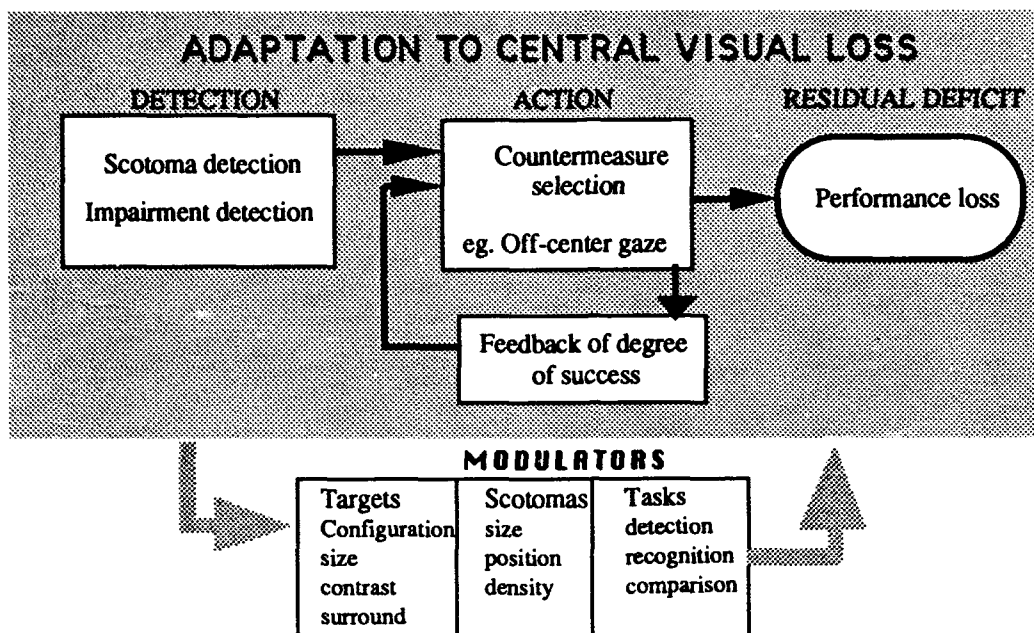


Figure 1. The model of adaptation to central visual loss begins with a change in the retinal receptors, due to Accident, disease, or light exposure, which leads to a detectable change in vision. A bright spot afterimage from light exposure or detectable loss of visual acuity leads to activation of adaptive processes. An experienced observer will begin off-center fixation in order to place the target of interest on an area of retina outside of the scotoma and monitors in some way whether this eccentric fixation strategy has a positive effect in reducing the scotoma impairment. With smaller targets, larger scotomas and more difficult tasks a residual visual deficit is likely.

fixation duration during search for acuity targets.

Scotoma characteristics

An absolute central scotoma is an area completely unresponsive to light. In a relative scotoma, an area with less severe dysfunction, there may be a contrast reduction or metamorphopsia in the visual targets (i.e., a change in visual signal geometry) which may be just as impairing as absolute blindness if the task requires acuity or visual function above that relative threshold (See Bertera, 1989, for examples of graded task difficulty and scotoma effects).

The size of scotomata associated with retinal disease or injury can vary enormously. A scotoma due to accidental laser exposure can vary from single laser burn size of 50 microns (Beatrice, 1982) upwards. For larger foveal centered scotomas (e.g., >2.0 degrees). The scotoma size may be affected by pulsed sources where there is a likeli-

hood that multiple burns or afterimages might be produced in a single incident, linked by some function of eye rotation, inter-pulse interval, and pulse duration. Further, multiple scotoma geometry may create a coalescing effect or a "fill in" of the dysfunctional area, perhaps similar to the perceptual filling of a blindspot (Kawabata, 1983), resulting in larger deficits than predicted by a simple additive model for laser spot sizes.

Asymmetry in eccentric viewing position

While plasticity is available for adaptation of peripheral viewing positions, subjects have strong preferences for selecting one viewing location over another. The reasons for preferences are not known. It has been determined that subjects sometimes position their eyes in ways which are either asymmetrical, not optimum, or seem to generate abnormal eye movements even after extensive practice. There are preferences in viewing position

in patient population with clinical scotomas in which the eccentric viewing adaptation has had years to develop

Timberlake, Mainster, Peli, Augliere, Essock, and Arend (1986) and Timberlake, Peli, Essock and Augliere (1987) using a scanning laser ophthalmoscope, identified acuity isopters around various visible abnormalities on the retina and these isopters were then related to the preferred retinal loci (PRL) used by patients for eccentric viewing. The PRLs were positioned near the scotoma boundary but not always in the area of best acuity. About 60% of patients show a stable PRL (Whittaker, Budd and Cummings, 1988) within a 3x3 degree area; the larger the scotoma the more likely are multiple eccentric viewing locations.. Cummings et al (1985) found that 72% of patients with a central visual loss had developed a single, strongly preferred viewing position outside of the scotoma. White and Bedell (1990) further determined that macular disease scotomas of 5, 10, or 20 degrees were associated with a preferred fixation area but rereferencing of eye movements to these areas was incomplete. Two earlier reports which measured eye movements with a scotoma, both with one subject, demonstrated some degree of eccentric viewing but without a clear preference for a defined eccentric viewing position (Zeevi, Peli and Stark, 1979; Whittaker and Cummings, 1986).

In a study of spontaneous adaptation to a simulated scotoma in six normal subjects, there was a marked preference to consistently position the scotomatous fovea out of the way to the upper right relative to the target (Bertera, 1992) even when subjects were free to look anywhere they choose. The subjects were required to hold the target in clear view with a 2.5 degree scotoma across their fovea which moved over background grid lines. This consistent, preferred fixation position translates into maintaining the target on the superior retina and as close to the scotoma border as possible, i.e. in the highest available resolution retina. It is probably no coincidence that clinical reports indicate that patients are much more likely to notice deficits in vision when treatment or disease creates visual loss on the superior retina. This

makes sense since the superior retina receives much more input from below the horizon field where there are more visual signals for daily activities.

The upper right spontaneous asymmetry during steady eccentric viewing position has not been explained by simple asymmetries in eye control for different positions around a target. Bertera (1992) tested a series of alternative fixation positions around the target while subjects viewed with the scotoma to determine if some oculomotor instability could be detected at unpreferred positions. While the percentage of eccentric viewing was about the same for the alternative positions, non-significant asymmetries did emerge in longer fixation duration and better average eccentricity for the upper right position. There are many asymmetrical functions and architectures across the retinal field (Estes and Wolford, 1971) that might be used to explain the left right asymmetry, such as, left-right biases from reading habits, cerebral hemisphere asymmetries for input and spatial attention, and the position of the optic nerve.

Scotoma nystagmus and drift.

Subjects show general instability in eye control with an increase in saccades and a high proportion of viewing time spent in error fixations, during the early phases of adaptation to a scotoma. After some adaptation period, eccentric viewing develops and near normal stability may return for steady fixation tasks measured by an increase in fixation duration. It has been generally assumed that establishment of a stable eccentric viewing position, and increased fixation duration, is a sign of adaptation to a central scotoma. However, stable eccentric fixation and prolonged eye fixation durations may set the stage for the onset of drift or the slow phase of scotoma nystagmus.

These slow movements during eccentric viewing range from drift movements, some lasting 15 seconds, to repeated nystagmus-like movements consisting of drift with a saccadic return, called "scotoma nystagmus". Unlike other forms of nystagmus (optokinetic or vestibular) this "nystagmus" can be interrupted with verbal instructions

to make saccades. The significance of such movements is that they redefine the eccentric viewing position as a track. The drift or scotoma track moves the average viewing position towards more peripheral or hyper-eccentric retina with poorer acuity. A drift or nystagmus track of 60 minarc would position the eccentric viewing point as much as twice as far away from the target as necessary, for example, with a 120 minarc radius scotoma.

Steinman and Cunitz (1968) detected such drift eye movement while two subjects used eccentric viewing with a physiological scotoma and implicated the drift in the fluctuating visibility of targets first noticed by Simon (1904). The scotoma was 20-40 minarc radius and corresponded to the subjects' low light physiological scotoma (a rod free area in the foveal region that forms a "blind" hole in dim light). The two subjects both made drift movements toward the target location followed by return saccades. One subject preferred an eccentric viewing position in the upper right while the other preferred the upper left.

Steinman and Cunitz (1968) suggested that the drift movements were all directed towards a target disappearance point and that the drift mechanism is guided by some retinal architecture or normal motor habit for fixation control. Whittaker, Budd and Cummings (1988) found drift eye movements with scotomas in three more subjects and showed that drift slow phase can be consistently towards other directions than the target, i.e., the normal fixation locus. Whether drift was target directed or not was idiosyncratic.

Bertera (1990) and Bertera (1991) measured eye movements during the early scotoma adaptation period and found repeated drift movements with normal subjects with simulated scotomas. Five subjects emitted drift eye movements with saccadic returns, but only after the initial period of adaptation when error saccades were minimized and the eccentric viewing position "settled down" to a stable vantage point. All the subjects showed periods exclusively of drift which brought the scotoma edge near an optimum position to the target followed by saccade returns, similar to jerk nystagmus. The eye may be drifting from 30-70 minarc/minute for more than half the

total viewing time.

Scotomas and target configuration

With several visible targets in a visual display the subject is faced with the problem of where and how to distribute adapted fixation responses. The adapted eye position control required to position and maintain a single target in an optimum area adjacent to the scotoma boundary may develop from immediate feedback by target disappearance inside the scotoma boundary or from the movement of a visible afterimage from a visible wavelength laser exposure, or from memory. The multi target problem for the subject requires a more global strategy: to choose an adapted eccentric fixation pattern which maximizes target visibility or performance, such as recognizing designated targets. It is clear that with a compact array of targets an eccentric eye position to one target may hide the remaining targets within the scotoma boundary. One solution would be to make a series of saccades each landing eccentrically so that targets are positioned in turn on the spared peripheral retina with optimum resolution.

During reading lines of text with a scotoma, Rayner and Bertera (1979) demonstrated that subjects are able to make a series of saccades which are adapted to the scotoma size to produce a progressive series of peripheral to peripheral saccades. The line of text provides a built in strategy to guide the adapted eye movements. However, in visual search with many targets or in monitoring a few target locations scattered around the display the subject must formulate a method for monitoring all the locations without such a stereotyped guide.

Multiple targets often require saccades to different visual field areas, rather than a fixed, stable eccentric viewpoint. The optimum saccade adaptation would be to shift or translate the landing position of the eye off the fovea to a single location, like a "neo-fovea", as near to the scotoma edge as possible for every eye movement. For some reason, subjects have great difficulty making such pure translational adaptations and they make many errors, either short or long of the correct "neo-

fovea". One hypothesis is that the error eye movements demand mixtures of translation and gain change strategies that limit adaptation because the two methods are mutually incompatible.

Rationale

The interaction of scotoma characteristics and target configuration needs to be addressed because eccentric viewing is the only unaided adaptation to loss of central vision. In general, two questions are important: what are the capabilities and vulnerabilities in oculomotor control during eccentric viewing, and, how does eccentric viewing interact with a range of target configurations?

This study was designed to further characterize adaptation to central visual loss by examining the development of eccentric eye fixation position, fixation duration changes and abnormal scanning patterns. Eccentric eye fixation or off center eye positioning relative to the target of interest was deemed of principal importance in analyzing adaptation. The working model for adaptation and visual loss (Figure 1) framing the present studies shows detection of visual loss and triggering eccentric fixations as the main mechanisms for overcoming deficits. If the subject has made an optimum adaptation to the loss of central vision, i.e. to the simulated scotoma, each change in eye position should place a target of interest on an area of working retina that is optimum for 1) information acquisition (generally the area with the highest remaining acuity), 2) eye position programming, or 3) avoidance of errors. To fully compensate for central visual loss, both the attentional focus of the fovea and the motor control of the eye fixation response must be oriented to a peripheral retinal location (Von Noorden 1967). Uncompensated visual impairments or incomplete adaptation results in residual deficits.

A major project thrust is to determine how eye movements adapt or change under scotoma conditions from focusing the fovea on targets to focusing the spared regions of the periphery on targets. A further objective was to determine how the scotoma interacts with the target size and position in the visual display.

METHODS

Subjects

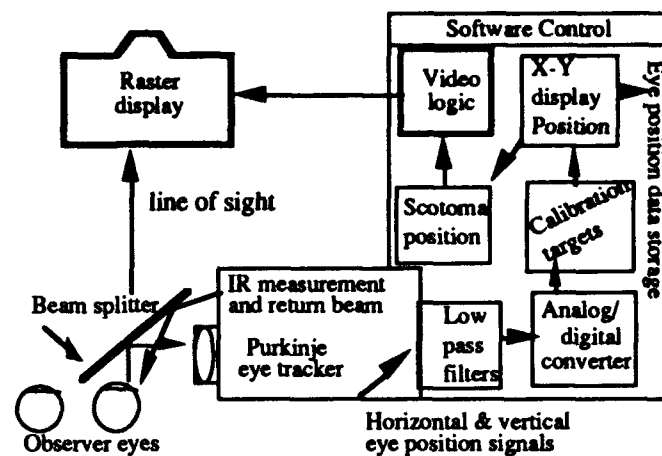
The subjects were between the ages of 18 and 45 were in good health and were free of ocular pathologies. Some (less than 10%) wore eye glasses and a correction lens was inserted into the optical pathway to compensate for their normal correction. They were given the informed consent procedure in the prescribed manner and were paid for participating at the rate of \$20 per hour.

Apparatus

The simulation of a central scotoma employs feedback from high accuracy eye position sensors and requires close coupling with computer data acquisition and visual display control. Horizontal and vertical analog eye position outputs from a Purkinje tracker (Crane, 1978) were used to control the scotoma position with a delay of approximately 4 ms. The analog outputs representing horizontal and vertical eye position were low pass filtered to limit an overshoot artifact characteristic of Purkinje trackers, digitized at 200-250 Hz and stored. Placement of the scotoma was accurate to 5 minarc or better and accuracy was checked before and after about 80% of trials. The right eye was used to position the scotoma since the tracker only records from the right eye. Some subjects steadied their heads with a dental mold to insure accurate eye movement recordings. Calibration targets were used to relate eye position voltages from the Purkinje tracker to the display screen coordinates.

The visual targets and the simulated scotoma were presented on a raster display. The use of raster technology instead of CRT displays and optical overlays supported objectives to enlarge the scotoma size, to develop a scotoma with graded edges (to attempt to grade visibility through the scotoma), and to generate multiple scotoma patterns. An integrated scotoma and search field, and

Figure 2. The scotoma simulator is diagrammed with Purkinje Tracker, computer control elements and raster display. Right eye positions are measured and the X-Y analog outputs are converted to gaze position relative to visual display using individualized calibration values. Scotoma movements which obscure the display imagery corresponding to a disk centered on fovea are accurate to within 5 minarc. The scotoma and visual display are integrated together within the same raster monitor.



the fixation calibration targets were presented on a raster display where the maximum working area was 12 degrees wide placed 79 cm directly in front of the subject (Figure 2). The scotoma position was updated at 71 Hz for most trials.

A target character disappeared, was replaced, or reduced in contrast when the scotoma boundary passed over it. The scotomas varied in size, generally from 30 to 120 minarc in radius, but all were centered on the fovea. The scotoma boundaries (Figure 3) were calculated after each eye position sample and any displayed imagery within the scotoma boundary was masked or erased. In graded edge or relative scotoma condition the elements within the boundary were replaced by a reduced contrast image. This replacement procedure maintained visual information about the spatial location of a static target while reducing its visibility. The displays used in these studies employed rasters with a white background and black foreground, the normal relation for text on paper. The display resolution was 1.7 minarc per pixel horizontal and vertical. The contrast was approximately 95% for targets outside of the circular scotoma boundary. For the relative scotoma edge the contrast was reduced to 40% and 20% in two annular rings each 20% of the scotoma radius deep. The approximate luminance of the background was 1.9- 3.0 cd/m² and the foreground was .06-.11 cd/m² depending on screen position. Delays less than 16 msec between eye movement and scotoma movement are not possible with commercially available video raster displays. A zero delay, the ideal, is only

possible in a case of true retinal lesion or with an afterimage from strong light sources. The delays in these studies ranged from 5-16 msec.

Procedures.

Normally, when an observer is looking around a display with many targets, the focus of attention at any moment is taken to be the foveal fixation point. When looking with a scotoma, the attentional focus is uncertain; determining the peripheral location from which information is being extracted, around the edge of the scotoma, is ambiguous when a visual field has many targets. In some of the present studies this ambiguity was reduced by passing a stream of search elements through a limited number of display locations. For example, with a single search element stream location a series of elements could be flashed successively, some of which were "targets" and some non-targets. The position of the scotoma relative to this information location could then be read continuously with much less ambiguity about the location of attention.

Target elements were presented in a serial, superimposed stream. For most of the work, streams of targets were presented at 1 or 2 locations around the display. The subjects were instructed to search for the occurrence of a target element and push a button on target recognition. Graduated search element sizes were tested from 10-20 minarc. The serial streams were presented at a rate of 1 to 4 elements per second. A minimum of 5-7 trials

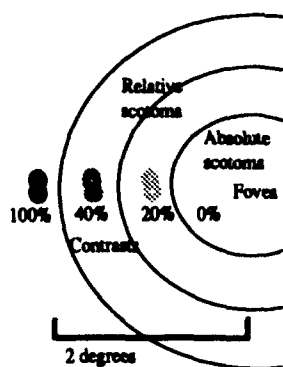


Figure 2. Graded edge (relative) scotoma with an absolute scotoma in fovea. In central fovea target contrast is 0%, simulating a retinal injury with progressive sparing of tissue and visual function into the near periphery. The presence of low contrast degraded target images in relative scotoma area tended to reduce eccentric viewing and appeared to promote impairments.

were presented for each scotoma size and target size combination.

The x-y eye position samples (consisting of 5,000-10,000 eye position samples per trial) along with the associated eye fixation durations were stored on computer disk. The samples were analyzed for the presence of fixations (typical criterion: dwell >100 ms within 10 minarc area), dispersion of fixations around the targets, eye fixation duration, and saccade length. Three zones were defined: zone 0 was anywhere inside the scotoma boundary, zone 1 extended from the scotoma boundary to 0.5 scotoma diameters, zone 2 included the space beyond zone 1. Error fixations, fell in zone 0, optimum fixations fell in zone 1 and hyper eccentric fixations fell in zone 2. The fixation types were counted and % viewing time calculated. Drift eye movements were examined for their direction and velocity. Data were eliminated from the analysis if there were any large head movements, track losses, or blinks.

DESIGNS AND RESULTS

In the first two studies subjects were free to select an eccentric viewing position which seemed easiest or most natural to them while monitoring either one target stream location (Experiment 1) or two horizontally placed targets stream locations (Experiment 2).

Experiment 1. Scotoma size and target size. Preferred eccentric viewing positions with a solitary target.

The asymmetry in subject selected eccentric viewing position found in earlier studies, where the upper right visual field is preferred for eccentric eye position, was replicated with different scotoma and target sizes. The instructions to the six subjects were specifically to look anywhere around the target they wished and that most people find "a position that seems easiest". The subjects preferred the upper right within a few minutes and were allowed to maintain this viewing position while adjustments were made in the target size and scotoma size. The target size was difficult to adjust to maintain a stable level of performance at 50% recognition of the targets, even at the preferred viewing position. For example, target recognition fell with larger scotomas, from 51% to 29% for the 30 and 60 minarc scotomas, respectively. The establishment of a scotoma size and target size combination which would yield a controlled performance level did not succeed probably because eye positioning strategies produced variable eccentricity and therefore variable target resolution.

Although the target stream location was stable, some subjects reported that their clearest view of the target was when it appeared to be drifting, probably caused by slow eye drift (1-2 degrees, 30-70 minarc/s amplitude) towards the target. The return saccades after each drift track put the eye in a hyper eccentric position, i.e., farther from the target than necessary to be outside the scotoma boundary. The average eccentricity was 60 minarc for the 30 minarc scotoma, 110 minarc for the 60 minarc scotoma and 155 minarc for the 120 minarc scotoma (Figure 4). The saccade length did not follow the eccentricities for average eye position and most saccades were shorter than the eccentricities because of the smaller corrective saccades which occurred after errors. Saccades increased with scotoma size, from 40 minarc in the no scotoma condition to 82 minarc for the 120 minarc scotoma.

The fixation durations generally declined with scotoma size, except for a peak at the 60

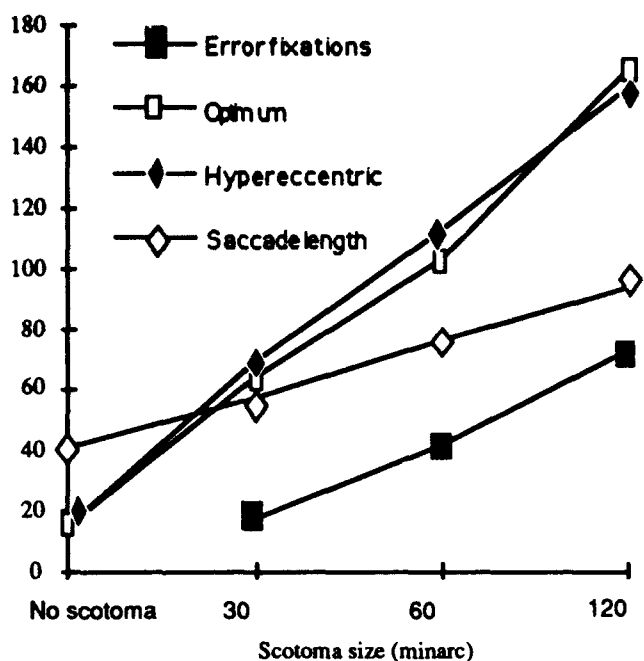


Figure 4. Fixation eccentricity and saccade length. Fixation eccentricity increases with scotoma size. Error fixations, where the target is inside the scotoma boundary, are shown in the lowest trace. Optimum fixations, positioned with the target within 0.5 of the scotoma radius from the scotoma boundary, also increase with scotoma size. Hyper eccentric fixations, greater than 0.5 scotoma radius from the scotoma boundary, also track the increase in scotoma size. Saccade length rises with scotoma size but does not follow the fixation eccentricity.

minarc scotoma. However, the variability was much higher for the optimum and hyper eccentric fixations for the larger scotomas, probably an indication of progressive loss of eye position control with the larger scotomas. The longest fixation durations were found for the no scotoma condition where the subject was monitoring a centrally placed target location.

Experiment 2. Scotoma adaptation modified by graded edge scotomas.

The visual display was programmed to reduce the contrast of targets within the edge of the scotoma, producing a relative scotoma for 3 subjects, instead of erasing them completely as with the absolute scotoma. The center portion of the scotoma remained an absolute scotoma in which the target

disappeared. Figure 6 shows a large loss in viewing time for a graded edge scotoma when compared with an absolute, sharp edged scotoma. The viewing time with no scotoma is 100% less the small intervals in which the eye is closed during blinks or during inattention. With a scotoma the periods in which the scotoma "covers" the target must also be subtracted from total viewing time.

The graded edge scotoma reduced target viewing time at all scotoma sizes. That is, the scotoma moved farther over the target before a corrective saccade moved the eye to an eccentric location. Figure 6 shows the high percentage of viewing time used in error fixations (Graded edge %time 0) which is nearly equivalent to the total eccentric viewing time for a sharp edge scotoma

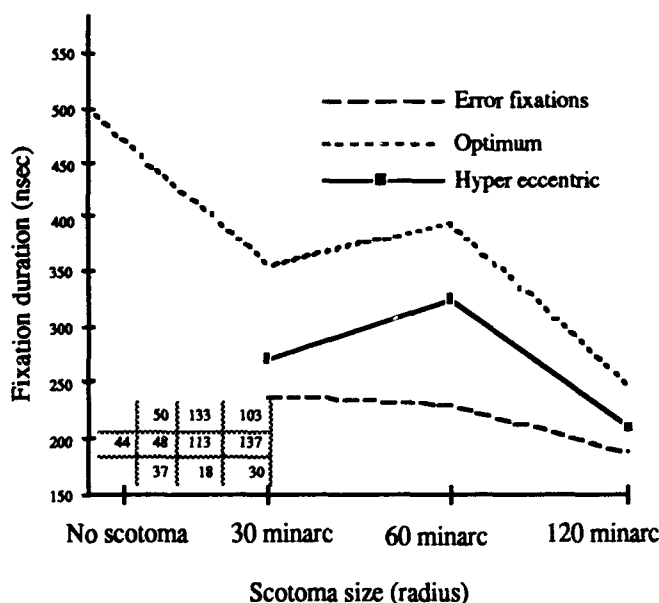


Figure 5. The average durations for the three fixation types are shown at each scotoma size. The optimum fixation durations (fixations from the Scotoma boundary to 0.5 the scotoma radius eccentricity) are the longest for the no scotoma condition. Fixation durations for optimum positioned fixations falls to about 350 msec at the 30 minarc scotoma. The hyper eccentric fixations (by definition absent in the no scotoma condition) start at about 260 msec at the 30 minarc scotoma and rise slightly with the 60 minarc scotoma. The three fixation classifications converge at the 120 minarc scotoma. Standard deviation in insert table. N=4.

(Sharp edge %time 2). Conversely, the viewing time for adaptive eccentric fixations is much lower for graded edge scotomas (Graded edge %time 2) and is nearly equivalent to the time spent in error fixations with a sharp edge scotoma (Sharp edge %time 0). Subjects moved their steady fixation position inwards from the scotoma edge to nearly the absolute scotoma edge. The adjustment matched the scotoma size closely. Target size had little effect suggesting that correctness or easy identification while subjectively appreciable were not controlling the eccentric viewing point maintenance.

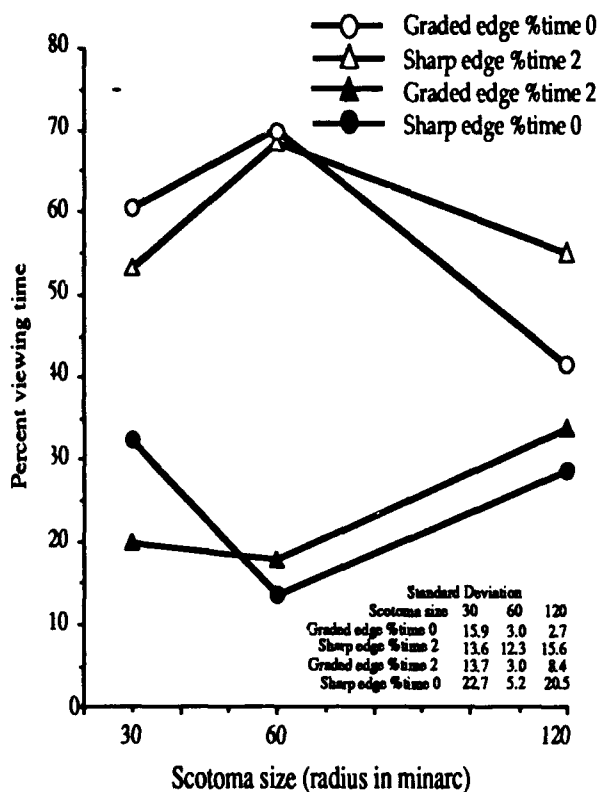


Figure 6. Loss of viewing time with graded edge scotoma. Viewing time (percent of total possible time) is shown for graded edge and sharp edge scotoma. Percent time was greater for the error fixations (open circles) than with the graded edge scotoma than the sharp edge scotoma. Conversely, percent time was greater for eccentric viewing (target visible) with the sharp edge scotoma (open triangles) than the graded edge scotoma. All three subjects showed this same relationship.

Fixation duration generally declined again with scotoma size (Figure 5), probably due to increased corrective saccades. The shortest fixations were found for the graded edge scotoma at the larger scotoma sizes, except for the eccentric fixations (Graded edge %dur 2) at the 120 minarc scotoma size. In general it seems clear that the graded edge scotoma has an impact on both viewing time and eye fixation duration.

Experiment 3. Preferred eccentric viewing positions with multiple targets: The effect of scotoma size and inter target distance.

Target configuration had a large effect on eccentric fixation adaptation, as large as the scotoma characteristics. The effect of three scotoma sizes and three inter target distances on eccentric eye position were tested while four subjects monitored two horizontally placed target streams (Figure 8). It was expected that eccentric positioning would deteriorate as scotoma size increased. In experiment 3 the subjects were free to adopt any strategy they chose for monitoring the two target positions.

The subjects generally avoided making saccades with all the scotoma sizes. All the subjects reported that they found accurate saccades very difficult to make with the scotoma. They attempted to position the center of the scotoma between the two targets whenever possible (Figure 9) so that both targets were visible at the same time. The eccentric eye position was adapted to the scotoma size and the inter-target distance. When the scotoma diameter was less than the inter target distance the fixation was centered between the targets, even when saccades would have brought the targets onto higher acuity areas of retina. As the inter target distance became less than the scotoma diameter, a condition which would have obscured both targets, subjects adapted by raising their eccentric fixation position so that the symmetric scotoma was evenly positioned and both targets were visible (See Figure 10).

The percentage of hits and the oculomotor variables were highly variable during the initial exposure because the subjects were hunting for a usable strategy. All claimed they were disap-

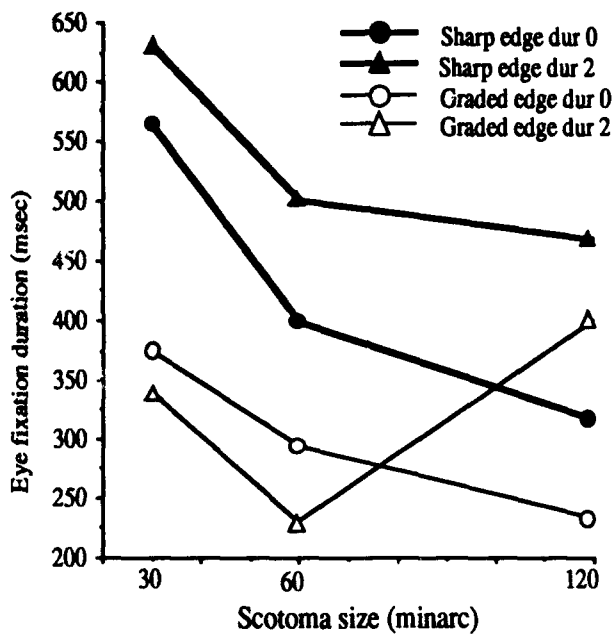


Figure 7. Reduction in fixation duration with graded edge scotoma. Mean fixation duration for the two scotoma types is shown across scotoma sizes. Fixation duration declined for both the graded and sharp edge scotoma as scotoma size increased. All three subjects showed these relationships. The only exception was an increase in graded edge scotoma duration for the 120 minarc radius scotoma.

pointed in their performance, were aware that they had formulated a distinct fixation position and reported that they were well aware that the target was disappearing when their eye moved. After the formation of a stable eccentric fixation point all the subjects showed some repeated drift movements. Of these, 3 of 4, volunteered that their clearest view of the target was when they made the target slide or wander, indicating the dominant direction of drift.

Two findings demonstrated the degree of adaptability of the eccentric eye fixation control. Eccentric eye fixation control appeared to be strategic and adapted to the size of the scotoma for positioning between two targets and in strategic drift termination. Figure 11 (left panel) shows an adapted fixation pattern which consists of drift downwards with repeated saccade returns upwards. While this pattern is typical it is clear that there is

a rather fine gap between the scotoma boundary and the end of the drift. It appears that the subject maintained the target in view by repeatedly terminating drift before the scotoma boundary crossed the target. This is remarkable since slow drift is generally considered to be outside of voluntary control. The second finding of interest is the "fit" of the eccentric viewing pattern with the target configuration (Figure 11, right panel). The subject detected the area where eccentric fixations would not obscure the target in earlier trials and maintained a viewing position there with few error fixations.

Experiment 4. Instructed saccades with multiple targets, landings inside, outside, left, and right of the two targets.

Instructing three subjects where to land their fixations relative to the two horizontally placed target locations was tried in an attempt to discover

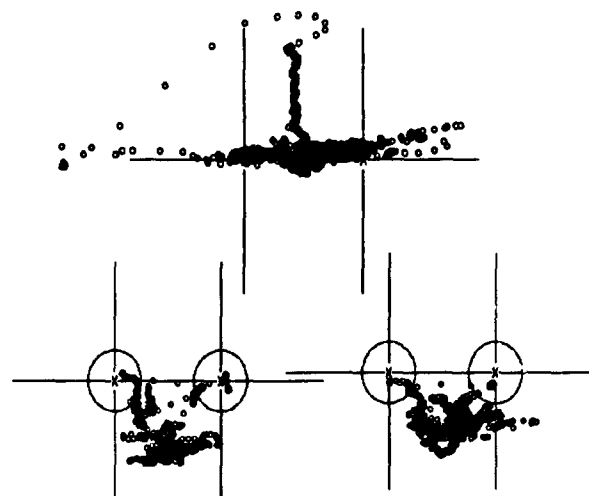


Figure 8. Eye fixation position samples are plotted around the two target stream locations (intersection of lines). Upper figure shows no scotoma condition with most eye positions between the two targets and long drift track running downwards. The circles in the lower two figures indicate the eccentricity required for targets to be visible outside of scotoma boundary (30 minarc radius scotoma). Fixations clustered below targets are atypical, most eccentric fixations are above and towards right side.

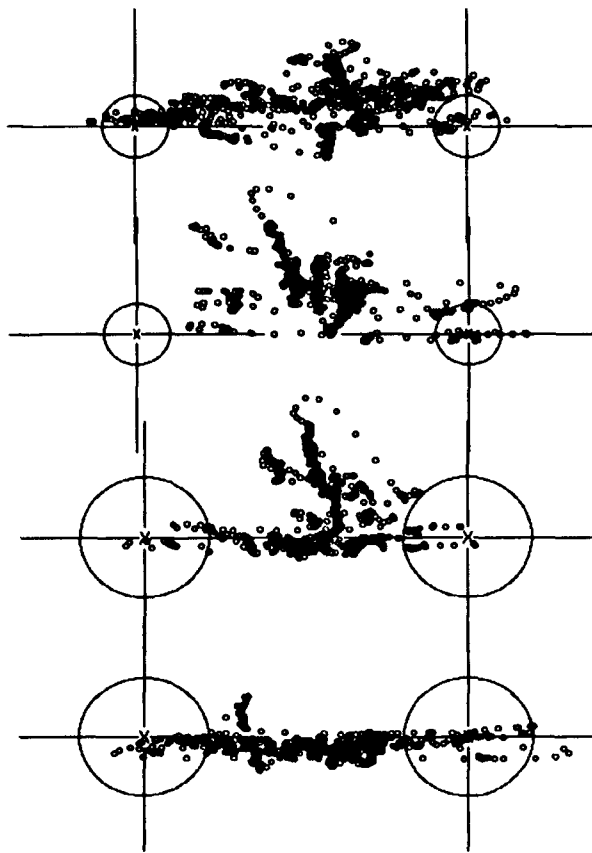


Figure 9. Eye position data from four trials are shown for two scotoma sizes (30 minarc, top two pairs, and 60 minarc, bottom two pairs). The subjects chose the mid position and drift tracks moving downwards with saccade returns were common. Bottom track has less drift because S made saccades to the optimum positions on the inside of the targets.

a position where accurate saccades would be possible with a scotoma. It was assumed that the preferred eccentric viewing position might not be the most stable or useful for eccentric fixation control even though such a vantage point might be perceived as "easier". When subjects were instructed to make repeated saccades to fixed positions relative to the two targets they produced inaccurate landings and performance deteriorated with larger scotomas (Figure 12 and Figure 13). Making saccades to positions on the inside of both targets, which would have produced the shortest saccades and highest resolution, was no better than

saccades directed to landing positions outside of the two targets which would produce the longest saccade length. Saccades instructed for landings to the right of each target or to the left of each target, required a consistent landing position, similar to the preferred viewing position of the single target condition. It seems clear that compelling the subjects to make eccentric saccades did not improve eccentric eye positioning. While eye positioning was more accurate for the "inside" fixation condition (Figure 12, top left panel) insofar as there were fewer error fixations, there is no clustering which might indicate intentional left-right positioning near the scotoma boundary. Rather, the saccades

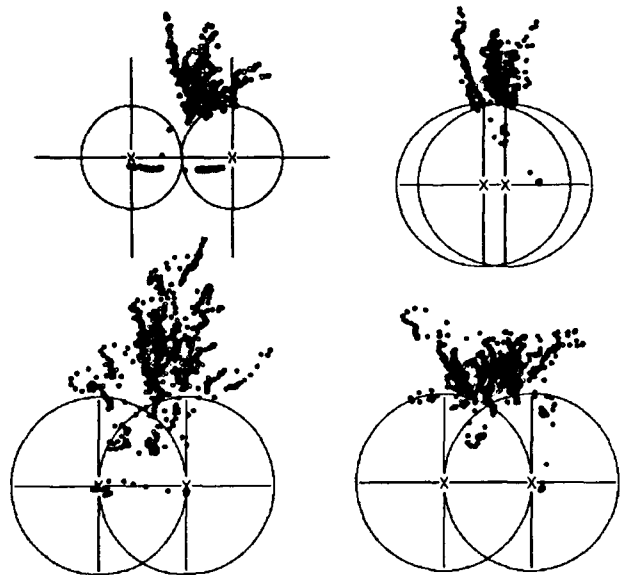


Figure 10. Eye fixation position samples plotted on two target arrays with 60 minarc scotoma in top left panel and 120 minarc scotoma in right and lower panels. The eye tended to drift downwards at 1-2 degrees/s. Targets were positioned so that neither target could be seen with fixations midway between the targets. Subjects rapidly adapted their fixation pattern when allowed to choose with most selecting the upper, upper right, or right side relative to the two target array when targets were positioned closely together.

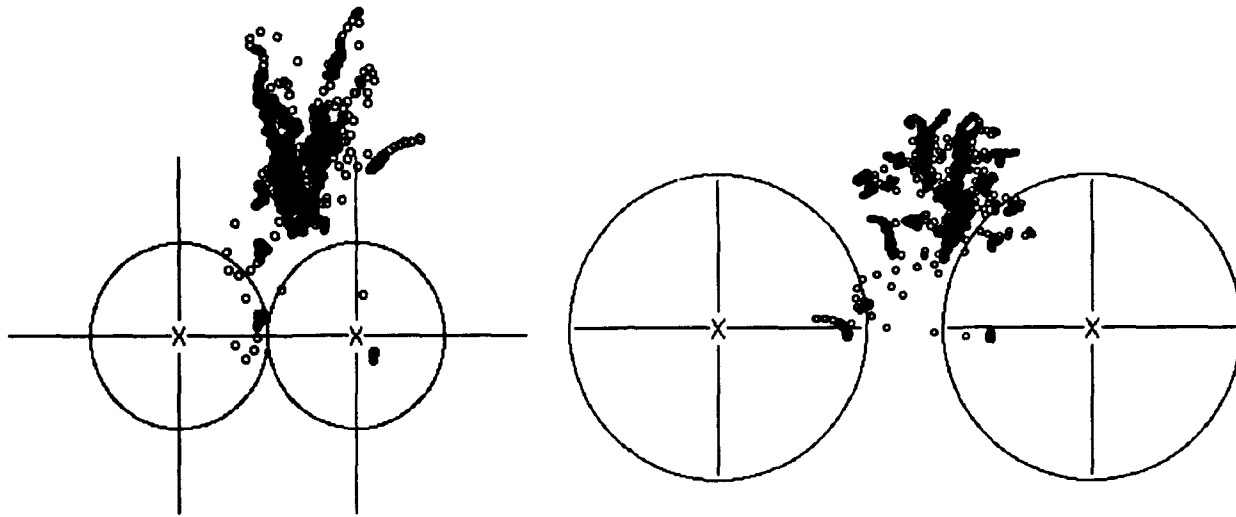


Figure 11. Adaptive eccentric fixation patterns are shown for 60 and 120 minarc scotomas. In the right panel there is a repeated down ward drift pattern with saccade returns. However, the drift terminates before the scotoma edge crosses the target. This is an example of strategic drift termination which indicates that eye drift and saccade returns are controlled in part by internal memory of scotoma radius, not just by the external signal caused by target disappearance. Compare with upper right panel, Fig. 10, in which drift track brings scotoma boundary over target, extinguishing it, before return saccade.

are probably undershooting the targets. It is well accepted that undershooting a target with saccades is much easier to learn than overshooting. Eccentric control appears especially poor for the left of target instruction trials shown in the top right panel (Figure 13). Subjects volunteered that they were aware occasionally of much poorer eye control but the reason is unclear. It seems reasonable that the saccades with the best positioning might be programmed quite independently of the target images once the subject has formed an adequate memory of the scotoma radius.

ANCILLARY FINDINGS

General agreement that intensive visual tasks can cause inhibition of blinking has not resulted in specifications about the task characteristics which modulate the rate of blinking. Lower blink rates and longer evaporation periods result in reduced ocular wetting and after the break up of the tear layer the corneal surface begins to dry. While ocular health is dependent on adequate corneal

wetting a more immediate concern during dry out periods is a reduction in acuity caused by changes in lens power and lowered target contrast caused by corneal surface hazing. These effects are more pronounced during soft contact lens wear, probably because water loss is greater from soft contact lenses.

During preliminary simulated scotoma runs it became clear that some subjects, who were allowed to wear their contact lenses, were inhibiting blinking and it seemed worth pursuing that their acuity might be reduced to some unknown degree during the eccentric viewing trials. This problem was explored by instructing subjects to fixate on a central acuity target (Snellen E) and indicate letter orientation with a button push as the contrast was changed in a staircase threshold paradigm (Timberlake et. al., 1992). Acuity was seriously impaired during the blink inhibition periods.

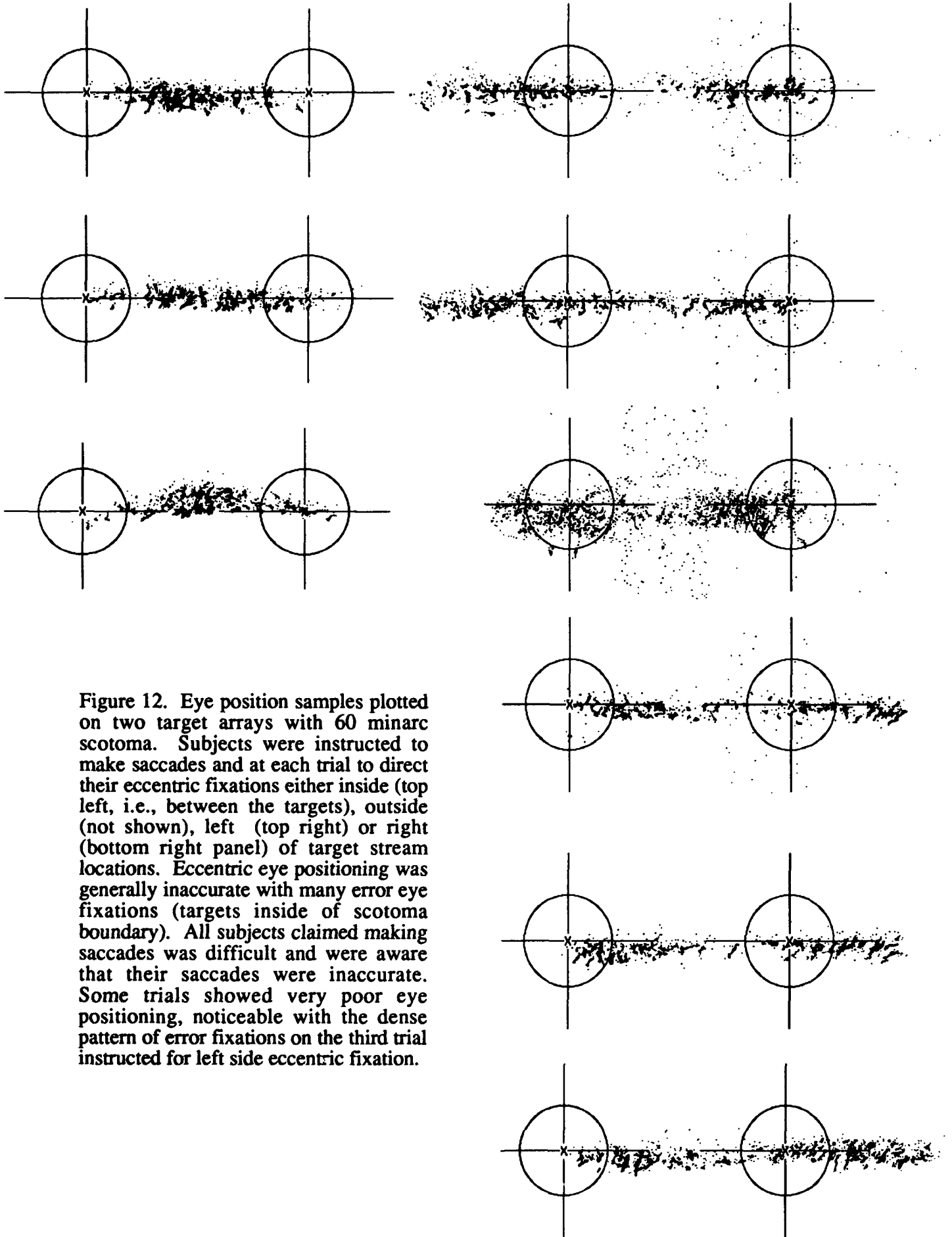


Figure 12. Eye position samples plotted on two target arrays with 60 minarc scotoma. Subjects were instructed to make saccades and at each trial to direct their eccentric fixations either inside (top left, i.e., between the targets), outside (not shown), left (top right) or right (bottom right panel) of target stream locations. Eccentric eye positioning was generally inaccurate with many error eye fixations (targets inside of scotoma boundary). All subjects claimed making saccades was difficult and were aware that their saccades were inaccurate. Some trials showed very poor eye positioning, noticeable with the dense pattern of error fixations on the third trial instructed for left side eccentric fixation.

DISCUSSION AND CONCLUSIONS

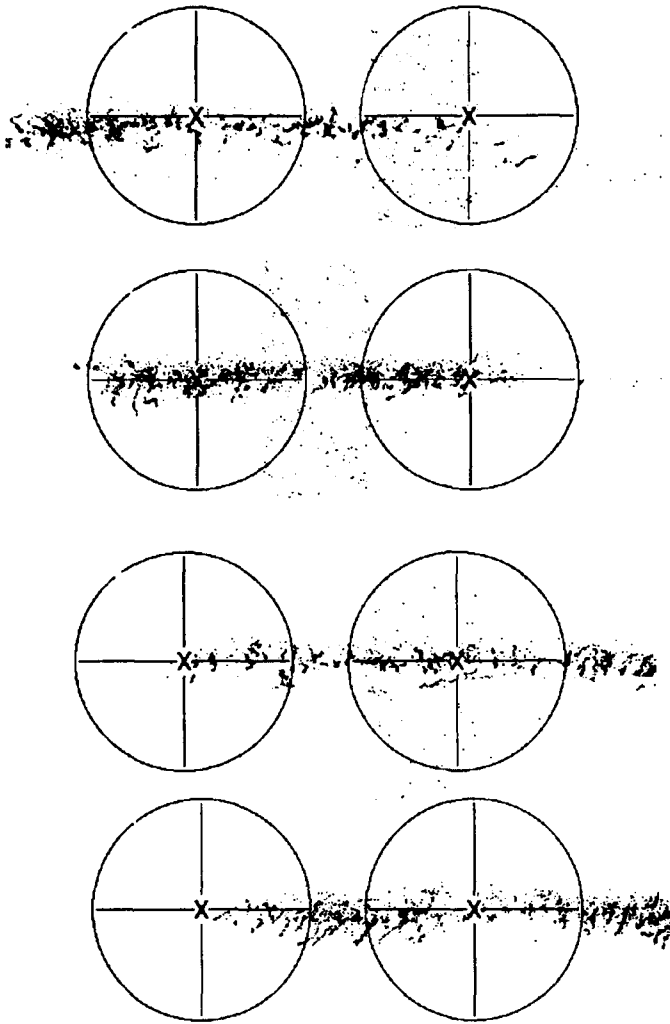


Figure 13. Eye position samples plotted on two-target arrays with 60 minarc scotoma. Subjects were instructed to make saccades to eccentric locations to either the left (upper two panels) and right (lower two panels). Most fixations were errors and brought the scotoma boundary across the target and many fixations were directed to the target center (reflexive error foveations). Performance did not improve with practice in any eccentric viewing positions.

Subjects adapted their fixation positions rapidly with a single target and preferred to position their fovea in the upper right visual field (corresponding to the target in the inferior nasal visual field). This finding replicates previous demonstrations of a bias in preference for eccentric viewing position. Several explanations for this asymmetry include neurological wiring or retinal architecture, reading bias, and oculomotor control. One implication of this asymmetry for scotoma compensation is that certain target configurations which accidentally favor this adaptation will be more efficiently processed and not as susceptible to central losses. While such an asymmetry in vulnerability dependent on target configuration has yet to be investigated it seems worth pursuing since all the subjects reported this preference, which was verified in the eye position records. A consistent preferred viewing position developed rapidly in these studies and was resistant to change due to task conditions. Positioning the scotoma should be optimized so that a candidate target is just outside of the scotoma area; as near to the fovea as possible to maximize acuity, particularly for targets with fine detail.

Several possibilities may be considered to explain this strong asymmetry. First, some motor habit, like a reading scan may bias the fixation position. Better stability or control may be achieved if the eccentric vantage point inhibits most errors (fixating the target with the scotomatous fovea). It could be speculated that the upper right position was preferred in free viewing and tended to produce less errors in instructed looking because reading habits are left to right in English. Eye movements going in the opposite direction, from right to left, may be better inhibited or less likely.

Consistency in using even an arbitrarily selected viewing position may allow less effort in maintaining compensation or in adding value to early learning and adaptation.

Two factors that can contribute to increasing the occurrence of target disappearance is poor control in positioning the scotoma edge during steady eccentric viewing (fixations) and delays in terminating the centripetal drift movements before the target crosses the scotoma boundary. Scotoma positioning control appears to be derived from the scotoma edge crossing the target and erasing or masking it. The graded edge scotoma may create weaker temporal transients at the scotoma edge which are not as useful for establishing the scotoma radius information. Strong transients from abrupt target disappearance at the absolute scotoma boundary can serve both to identify the size of the scotoma and its range from the target and as an immediate stimulus for a return or corrective saccade. The diminished temporal transients as the relative scotoma edge crosses visual targets may reduce or delay the value of the scotoma edge information. This degradation may account for the poorer eccentric control found in Experiment 2, in which subjects spent more than half the possible viewing time with the target in reduced contrast within the scotoma boundary.

Tailoring eye movements patterns to the configuration of multiple targets in a display is an ordinary problem in visual search and subjects are used to the common sense strategy of looking back and forth between two equally probable target locations. While shifting from fovea to a single eccentric viewing location is relatively easy with one target as demonstrated in Experiment 1, making eccentric saccades is much more difficult. This is consistent with the findings of Heinen and Skavenski (1992) using a monkey model with retinal lesions in which stable eccentric fixation position adapted but saccades did not. When given no specific instructions to make saccades, human subjects prefer a static viewing position strategically selected so that both targets are visible. This strategic positioning to avoid making saccades with a scotoma occurs across a wide range of scotoma sizes in Experiment 3.

Instructions to make saccades between two targets and to use specific viewing positions seemed to produce uniformly poor eccentric viewing in Experiment 4. Peripheral to peripheral saccades

are incompatible with two normal visual motor patterns. First, saccades which land targets on a consistent portion of the periphery instead of fovea violates a lifelong habit and perhaps neurological wiring as well. Second, the usual response to a target intended for fixation which by some error lands on peripheral retina is a corrective movement to reposition it on the fovea. Therefore, both the normal fixation pattern of fovea to fovea landing, and the normal peripheral to fovea corrective pattern, make peripheral saccades more difficult as a consistent central field scotoma adaptation.

The evidence that peripheral saccades result in frequent reflexive foveations with multiple targets is clear from the poor eye control for a variety of landing sites. Attempting to maintain a stable vantage point in between two targets is a workable strategy if the resolution is sufficient for recognition at a mid-point position. Since none of the peripheral saccade strategies produced a satisfactory adaptation in Experiment 4, it seems reasonable to pursue the estimation and establishment of efficient compromise vantage points for eccentric monitoring with central scotomas. An important qualification must be the subject's ability to estimate the losses in performance from under sampling the most distant target locations.

Another strategy for compensating for the scotoma is to attempt to use the reflex foveations, which seem so difficult to inhibit with saccades, to simply designate the target of interest. It is possible that an electronic aid could use such target coordinates to shift the target image area to a spared retinal locus with adequate resolution to maintain performance.

MILITARY SIGNIFICANCE

The widening use of lasers for sighting, range finding, and communications poses a threat from eye injuries and flash effects during combat and training exercises.

Personnel trained in adaptive responses will better maintain their effectiveness after laser exposure by effectively utilizing spared regions of retina. Methods for augmenting natural adaptive responses

like stable eccentric viewing and reducing maladaptive ones like error fixation and drift may assist in maintaining effectiveness after laser exposure. Detecting individuals vulnerable to maladaptive responses from visual loss can be determined with screening methods developed from the simulated scotoma method. An example is scotoma drift or nystagmus interacting with a normally benign congenital nystagmus.

Results will also be useful in detecting vulnerability in instrument or display design after laser exposure reduces central vision. For example, scotomas and adaptation movements may generate autokinetic movement in night vision displays or in impoverished scenes like desert terrain. The research outcomes may be applied to display design either as a countermeasure to scotoma effects, or to improve display visibility under degraded visual conditions from movement, vibration, or atmospheric haze.

Finally, lowered acuity during blink inhibition in contact lens wearers has implications for contact lens use in military and civil aviation. The effects of water loss on lens power and contrast reduction could be substantially increased and the onset accelerated by dehydrated environments which might be common, especially in deserts and high altitude flight. Acuity loss under intensive visual demands is perhaps a worse case. Losses might be even greater for tasks requiring substantial eccentric target detection or under low contrast visual field conditions such as target detection against clouds or camouflage.

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